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THE STATE UNIVERSITY
OF NEW JERSEY

Simulation of NAPTF High Tire Pressure Tests with Advanced Finite Element Modeling

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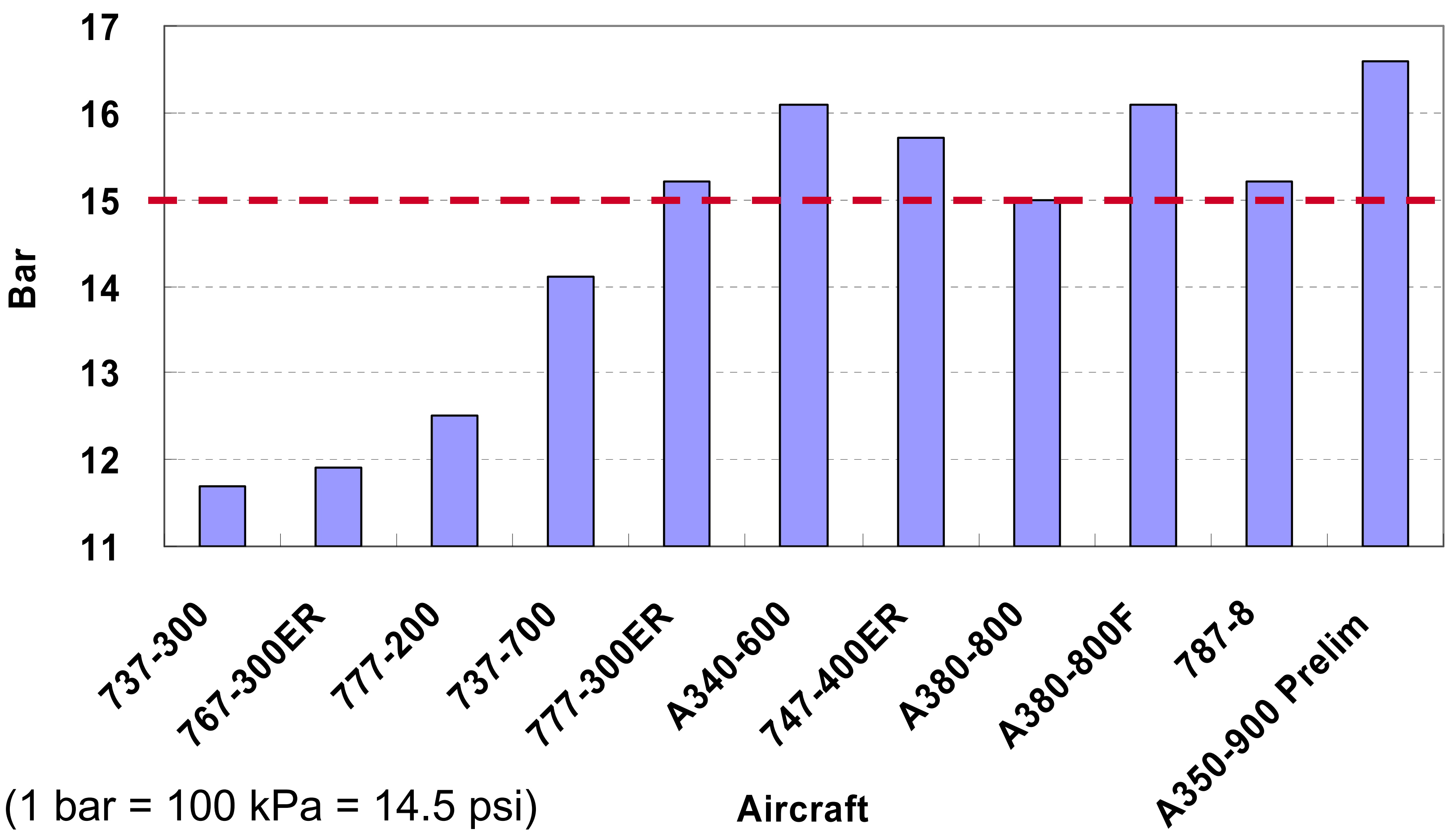
Aircraft Tire Pressure Trend



(1 bar = 100 kPa = 14.5 psi)

(*After C. Fabre, 2009*)

Objective and Scope

- Develop a 3-D viscoelastic finite element model for airfield pavement test sections at NAPTF

- Evaluate effect of aircraft tire pressure on pavement responses and rutting using different temperature profiles

  - 1.45MPa (210psi) vs. 1.69MPa (245psi)

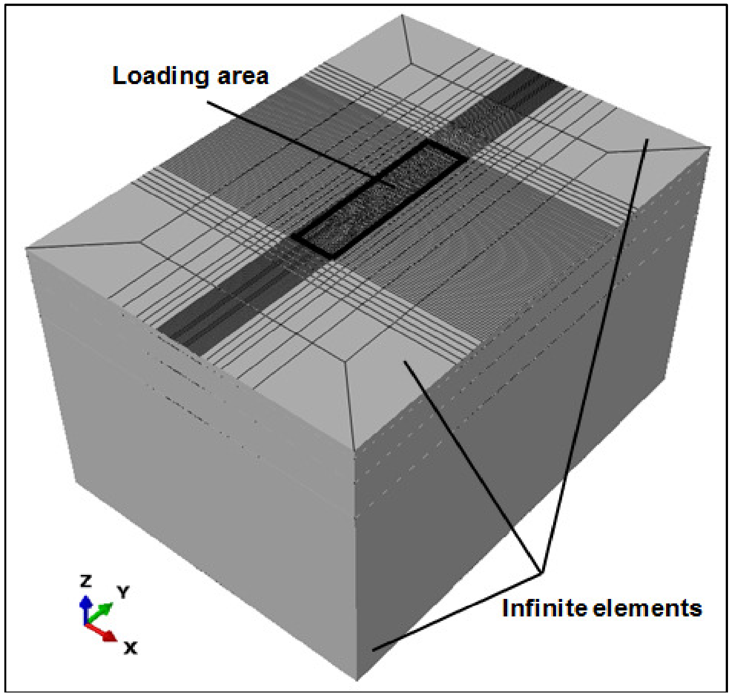
Calculation of Pavement Response

- **Layered Elastic Theory**
  - ❑ Simple loading and material assumption
  - ❑ Public software available
  - ❑ Fast computation speed

- **Finite Element Method**
  - ❑ Complex loading condition and material properties
  - ❑ Flexible geometry and discontinuities (joint, crack, interface, interlayer, et al.)
  - ❑ Large computation resource and time

3-D FE Pavement Modeling

- Moving tire load with pre-defined contact area and stress
- Quasi-static or dynamic analysis
- Viscoelastic asphalt layer
- Nonlinear anisotropic unbound layer
- Frictional interface



Element Size and Boundary Conditions

- **Element vertical size:**
  - 12.7 mm for HMA layer
  - 40-50 mm for base layer
- **Element horizontal dimension:**
  - 10-20 mm in the transverse direction
  - 40 mm in the longitudinal (moving) direction
- **Infinite elements used to reduce degrees of freedom and create “silent” boundaries**
- **Coulomb frictional interfaces are used**

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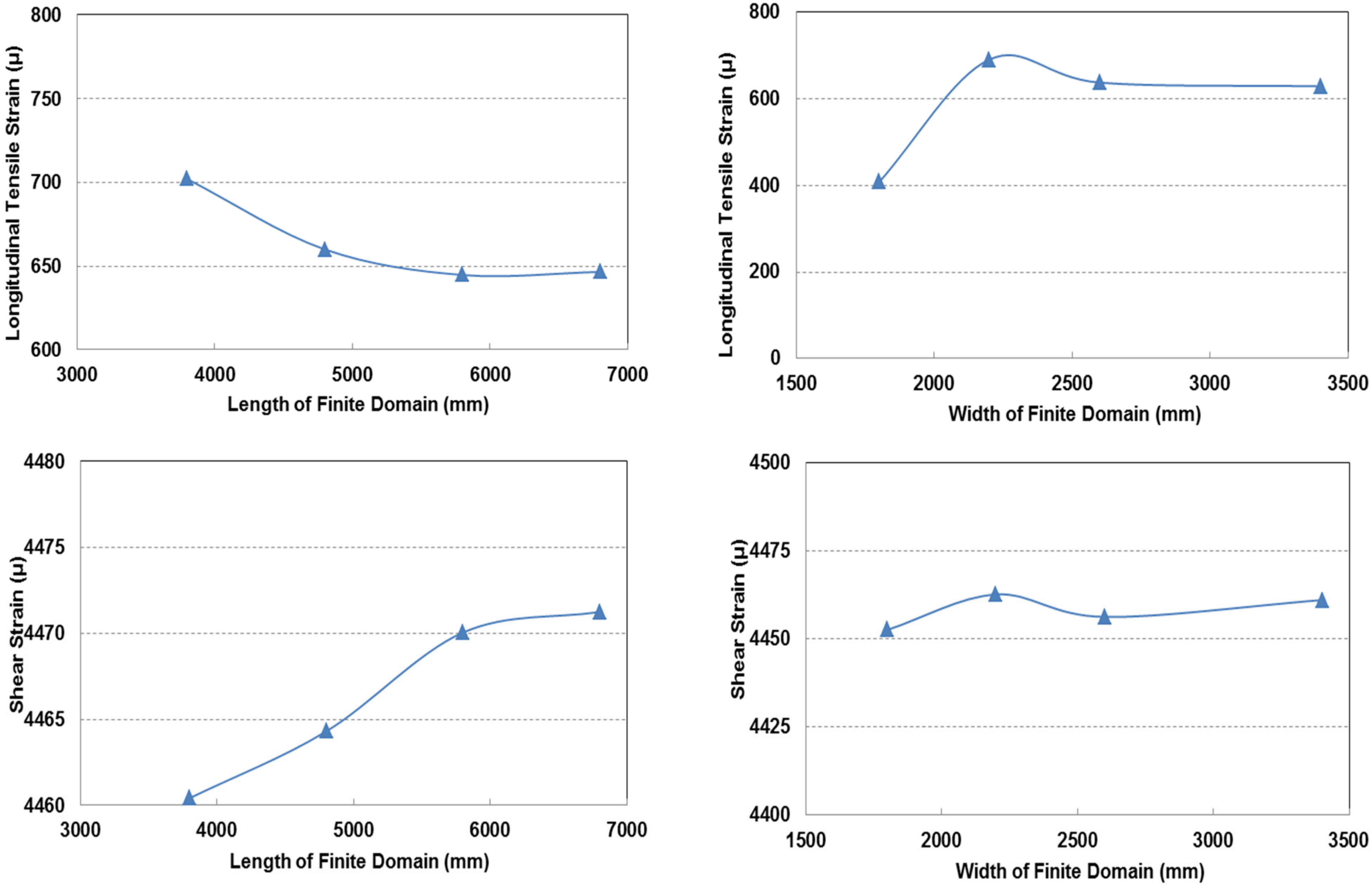
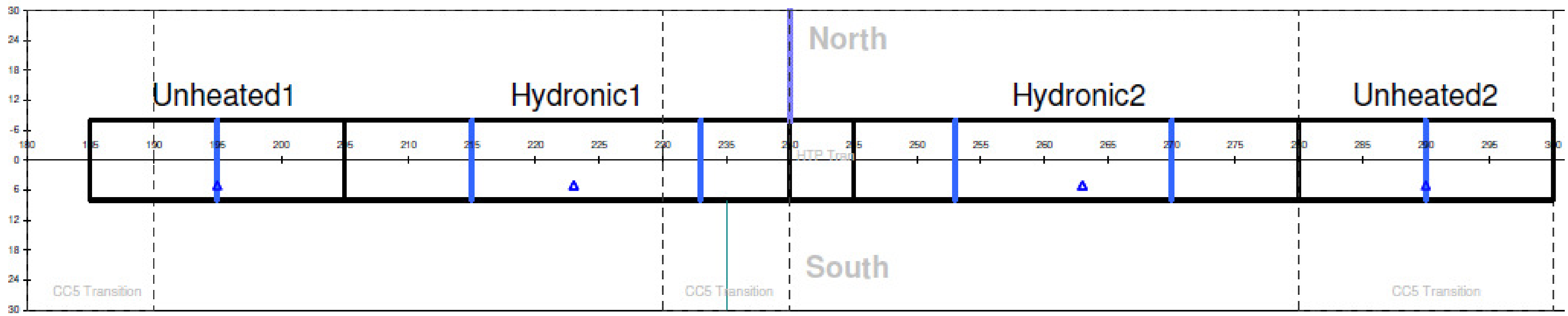
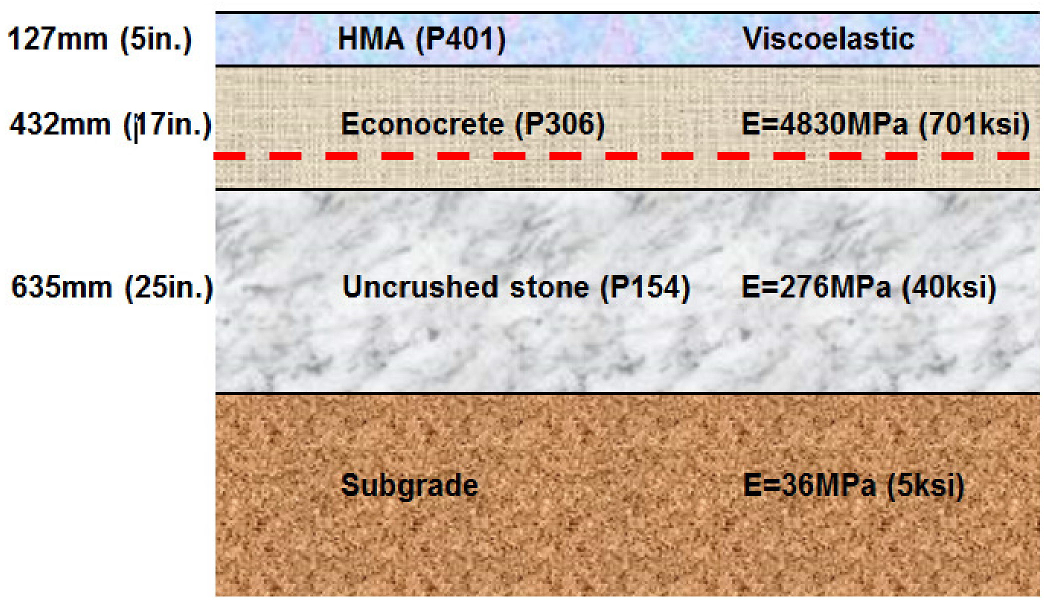
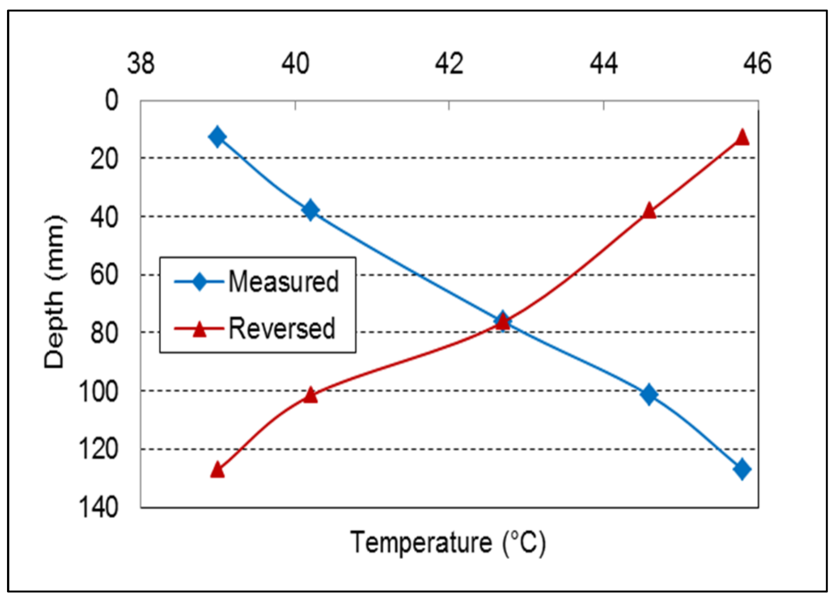
Determination of FE Model Size



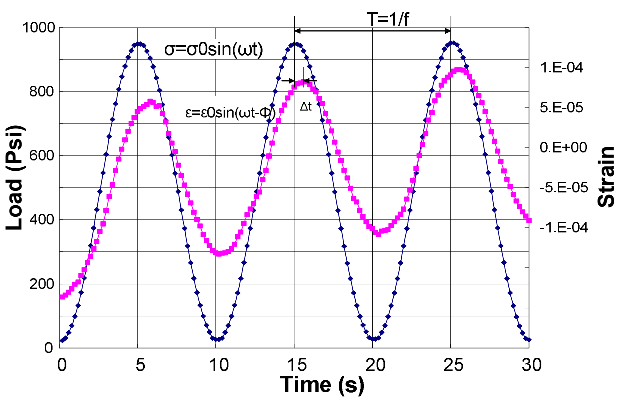
Pavement Structure

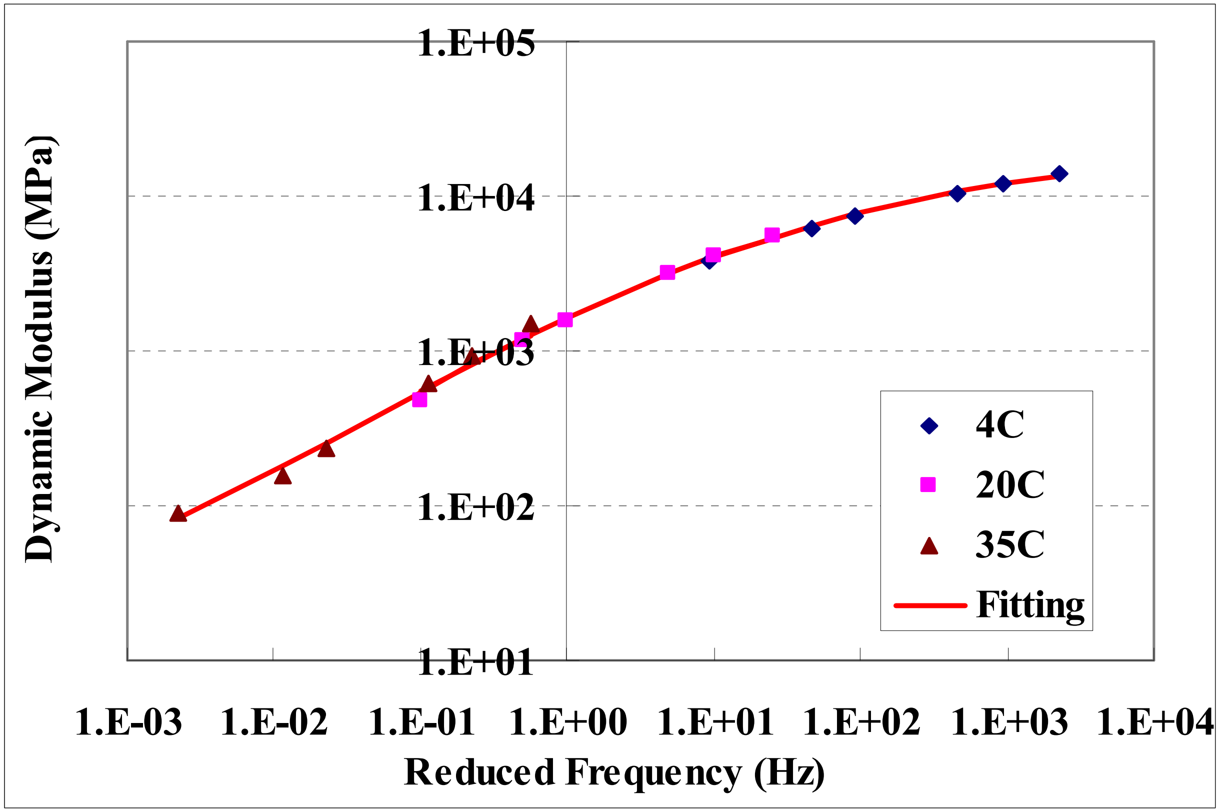






Material Characterization

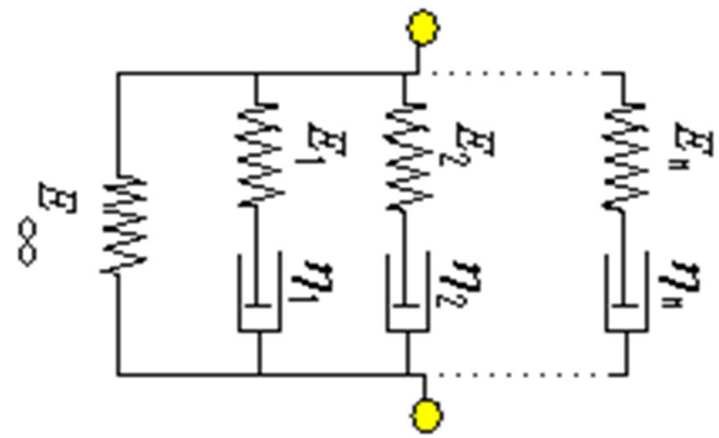




HMA Linear Viscoelasticity

- **Generalized Maxwell Solid Model: Consists of one spring and n Maxwell elements connected in parallel**

$$E(t) = E_0(1 - \sum_{i=1}^{N} E_i(1 - e^{-t/\tau_i}))$$



where,
E(t) is relaxation modulus;
E_0 is instantaneous modulus;
E_i and τ_i are Prony series parameters; and
t is relaxation time.

- **Relaxation modulus is converted from dynamic modulus and expressed as Prony Series**

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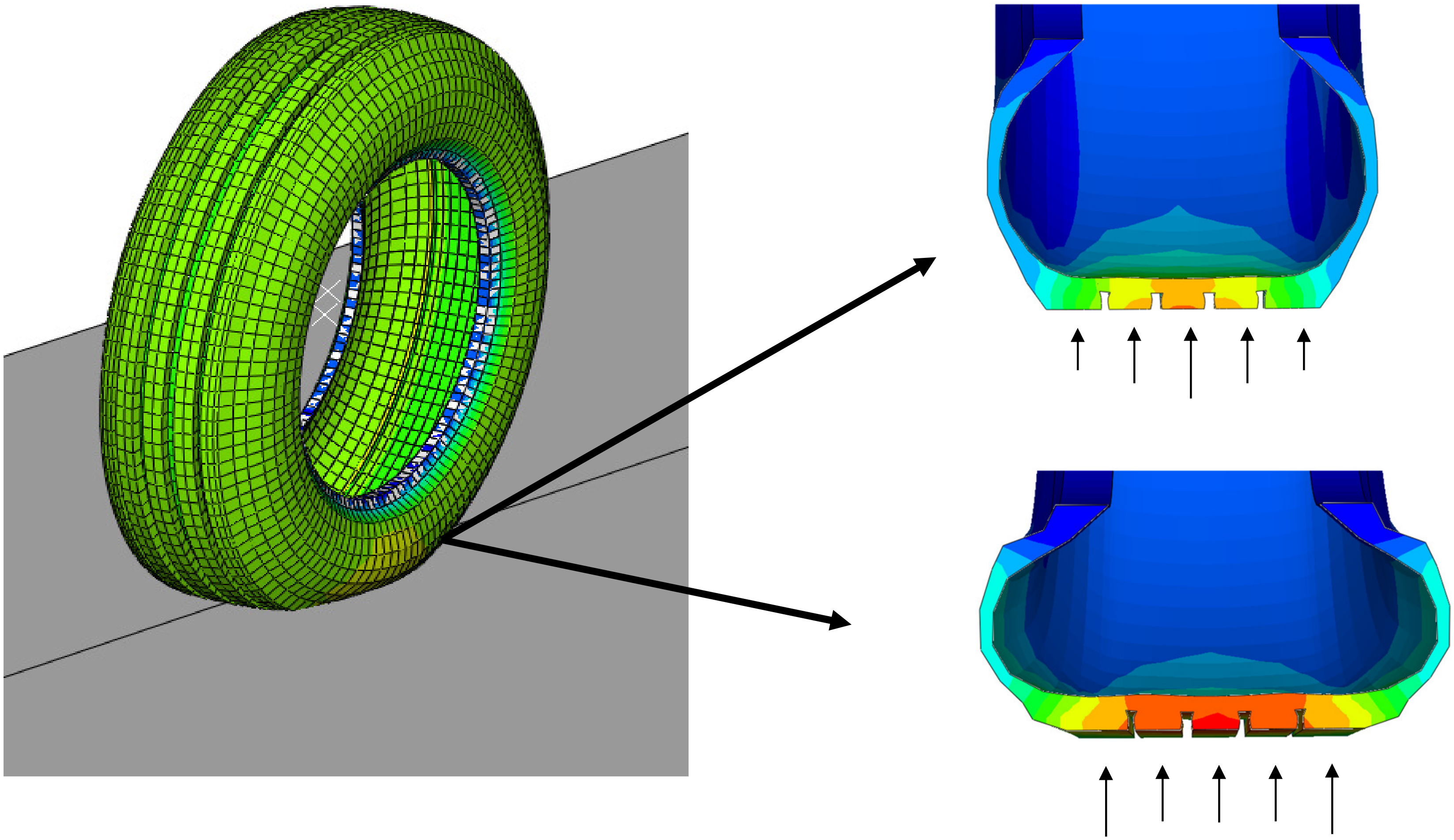
Non-Uniform Tire Contact Stress



Wang, H., I.L. Al-Qadi, and I. Stanciulescu, Simulation of Tire-Pavement Interaction for Predicting Contact Stresses at Static and Rolling Conditions,. International Journal of Pavement Engineering, Vol. 13, No.4, 2012, pp. 310-321

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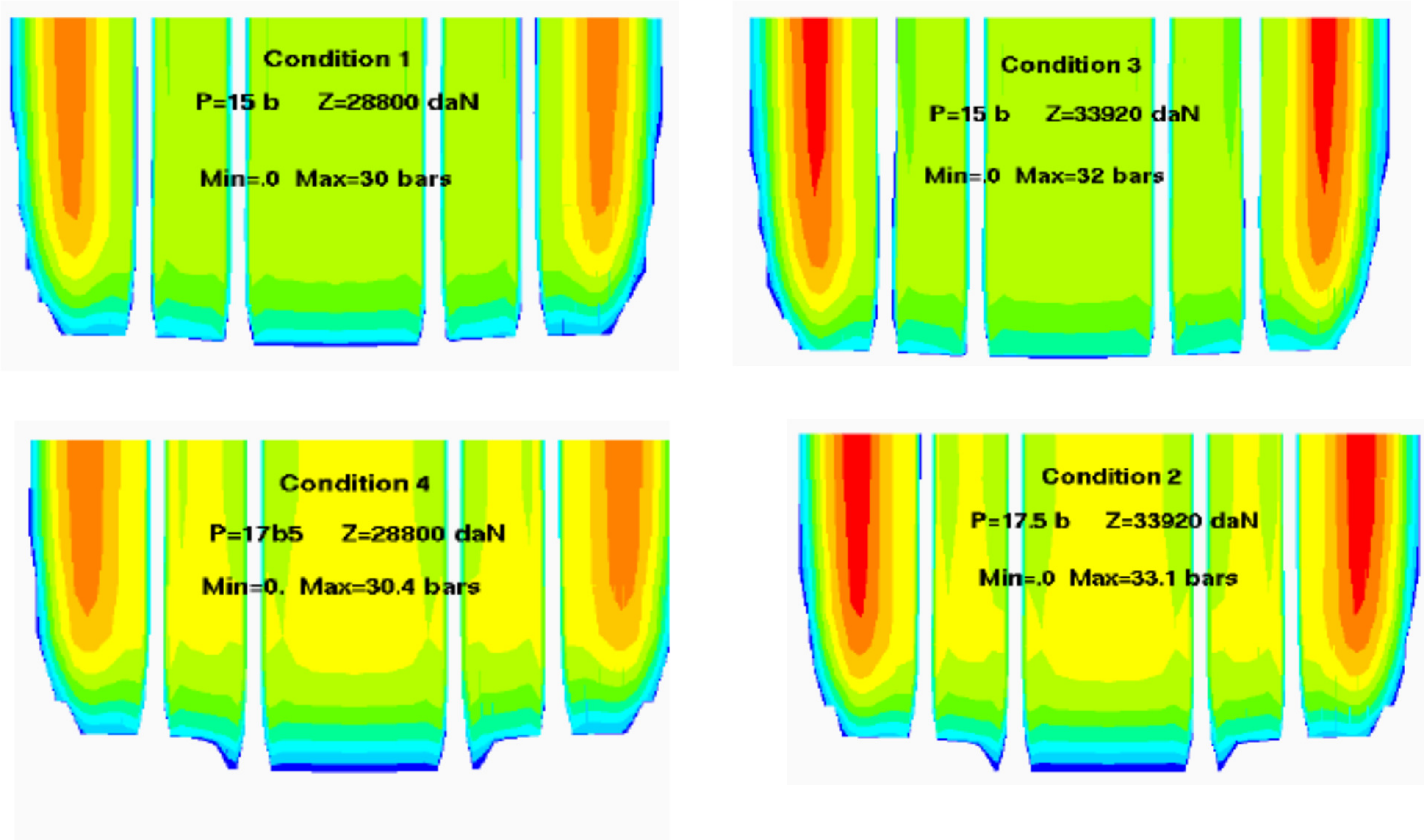
Changes in Tire Contact Pressure under Aircraft Load

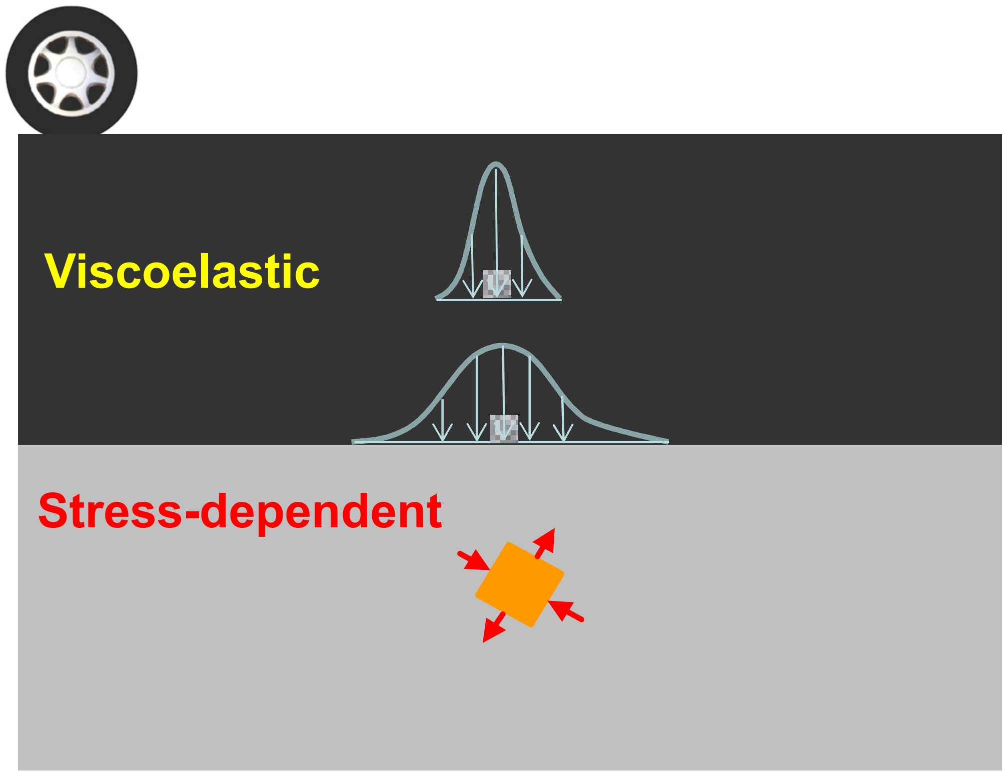


100daN = 1kN = 0.225kip 1 Bar = 100kPa = 14.5psi (*After E. Rolland, Michelin*)

Non-uniform Pressure Distribution
(1.69MPa and 1.45MPa)

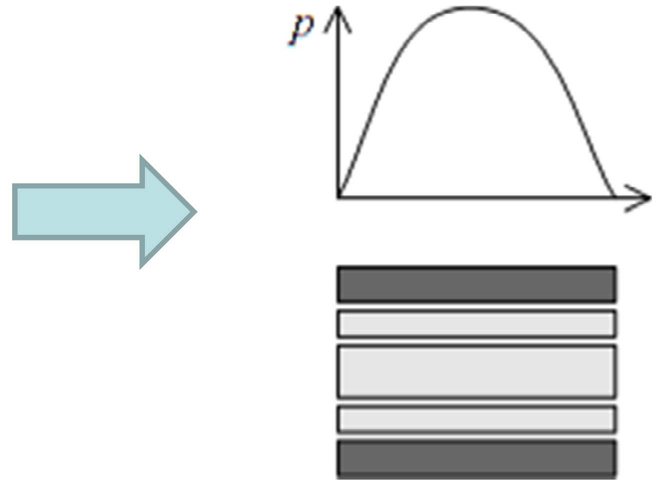
Contact pressure assumptions		Contact width (mm)	Contact length (mm)	Peak pressure (MPa)
Non-uniform	Rib 1	60	440 / 520	4.23 / 3.63
	Rib 2	50	440 / 520	2.11 / 1.74
	Rib 3	120	440 / 520	2.11 / 1.74
	Rib 4	50	440 / 520	2.11 / 1.74
	Rib 5	60	440 / 520	4.23 / 3.63
	Groove	15	440 / 520	0

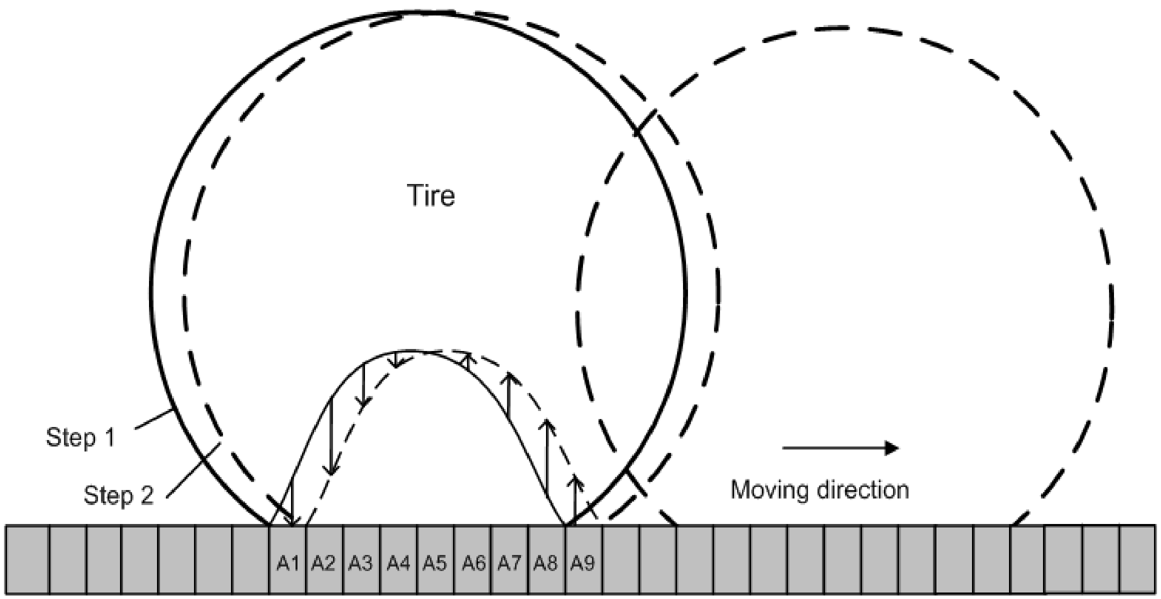
Importance of Moving Load

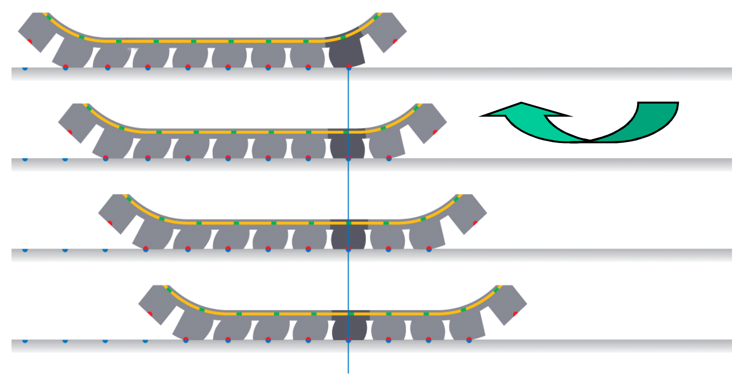


- **Loading time varies** at various pavement depths and directions
- **Principal stresses rotate** under a moving load

Simulation of Tire Loading







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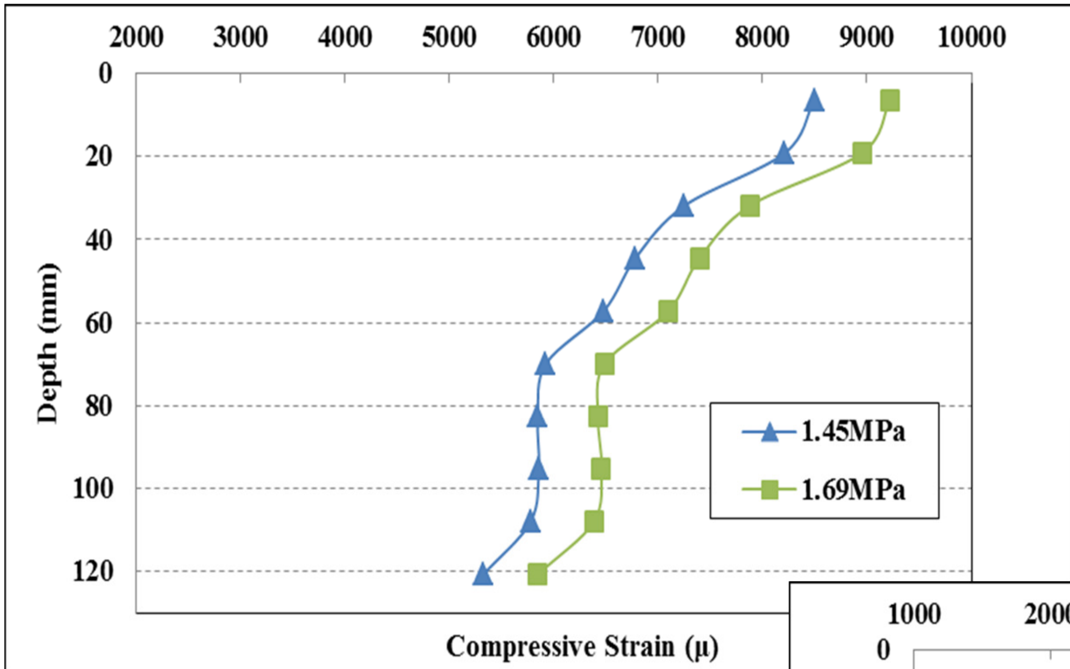
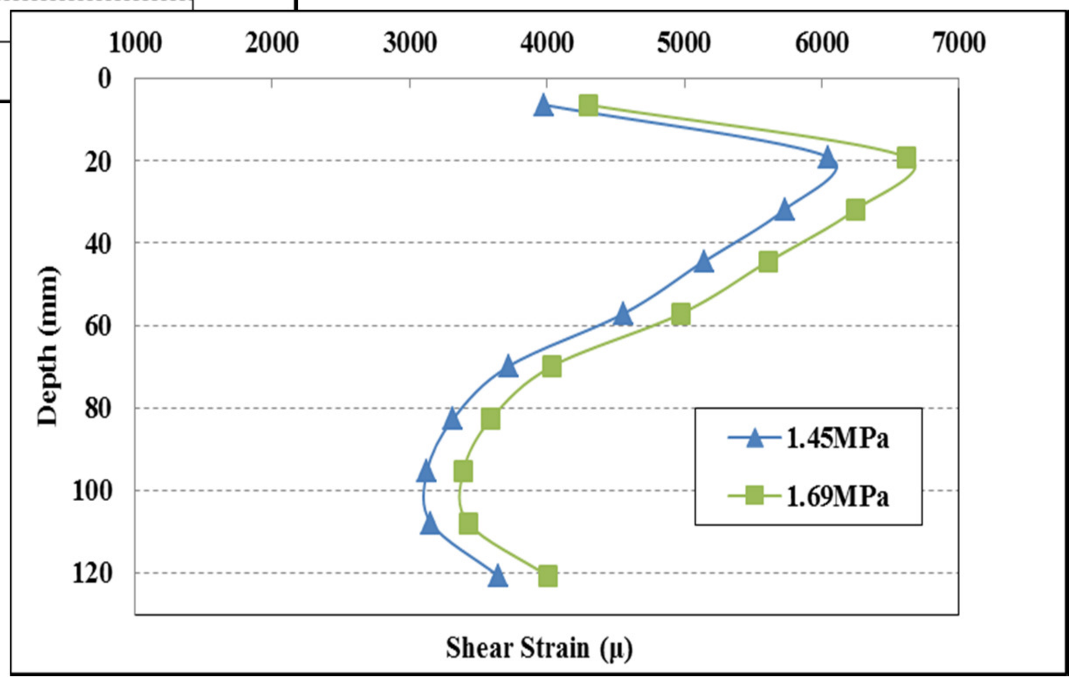
In-depth Strain Distribution

(measured temperature profile at NAPTF)





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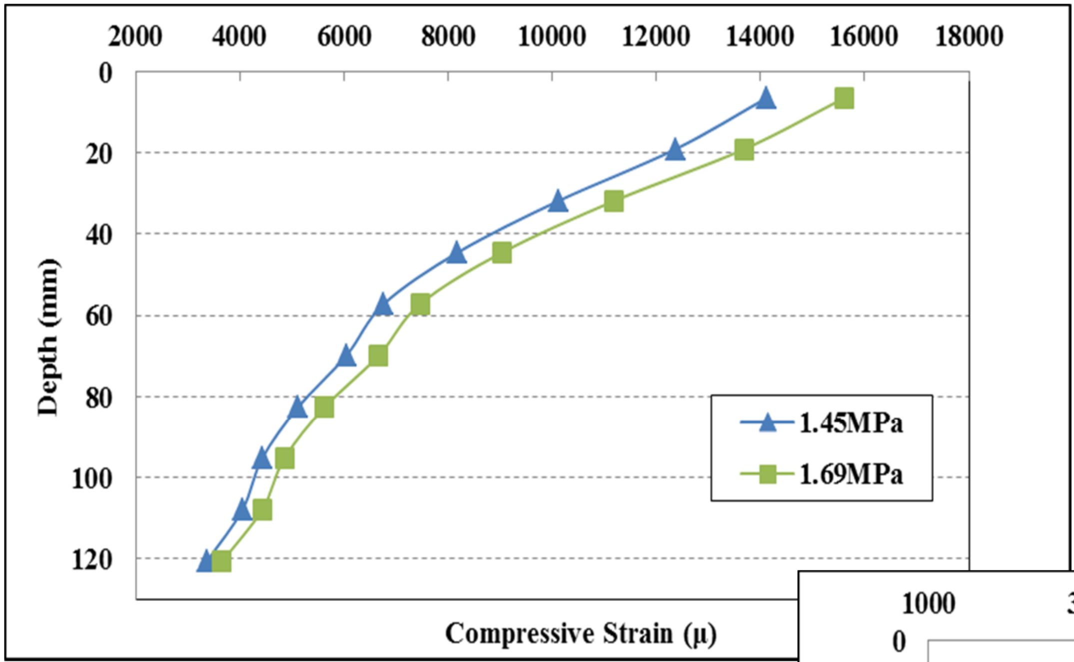
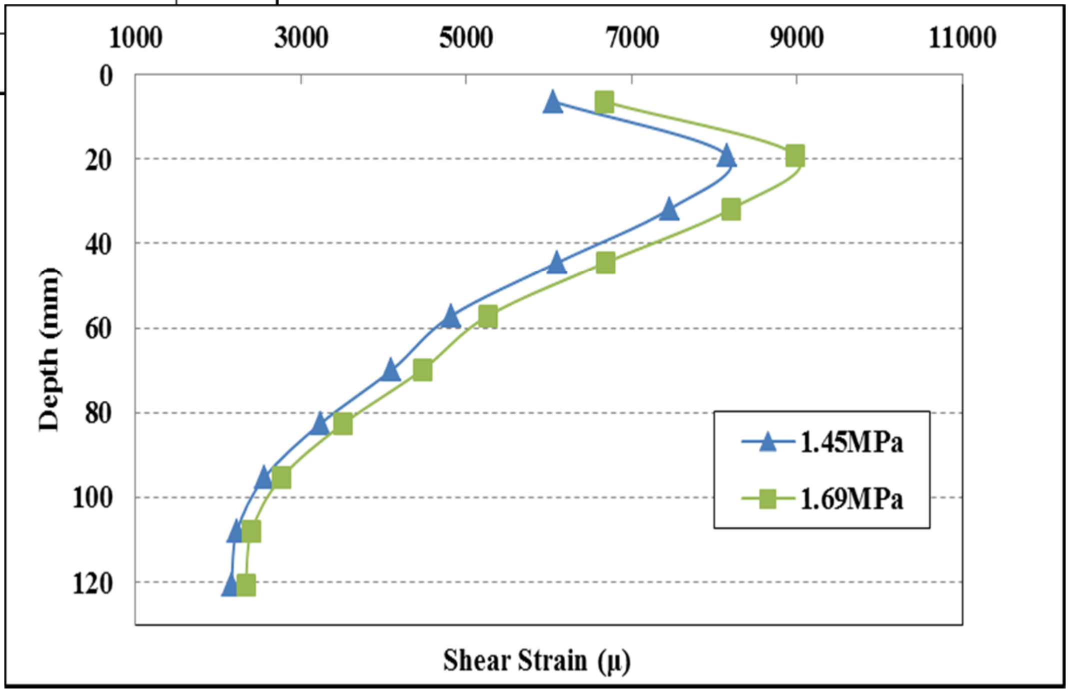
In-depth Strain Distribution

(reversed temperature profile at NAPTF)





Effect of Tire Pressure on Responses

Tire load: 272.7kN (61.3kips)	Measured Temperature Profile			Reversed Temperature Profile		
Tire pressure (MPa)	1.45	1.69	Change	1.45	1.69	Change
Critical tensile strain (μ)	1068	1339	+25%	899	1101	+22%
Shear strain (μ)	6049	6617	+9%	8158	8891	+10%
Compressive strain (μ)	8496	9225	+9%	14119	15614	+11%
Deviator Stress (kPa)	2107	2489	+18%	1823	2154	+18%

Calculation of Rutting Depth (MEPDG)

$$\frac{\varepsilon_p}{\varepsilon_r} = k_1 * 10^{-3.4488} T^{1.5606} N^{0.479244}$$

$$k_1 = (C_1 + C_2 * depth) * 0.328196^{depth}$$

$$C_1 = -0.1039 * h_{ac}^2 + 2.4868 * h_{ac} - 17.342$$

$$C_2 = 0.0172 * h_{ac}^2 - 1.7331 * h_{ac} + 27.428$$

where,

k_1 = function of total asphalt layers thickness (h_{ac}, in) and depth (*depth*, in) to computational point, to correct for the confining pressure at different depths

$$RD_{AC} = \sum_{i=1}^{N} (\varepsilon_p)_i \cdot \Delta h_i$$

RD_{AC} = rut depth at the asphalt concrete layer
N = number of sublayers
$(\varepsilon_p)_i$ = vertical plastic strain at mid-thickness of layer i
Δh_i = thickness of sublayer i

Calculation of Rutting Depth (AI)

$$Log\left(\frac{\varepsilon_p}{\varepsilon_r}\right) = -6.631 + 0.4354 Log(N) + 2.767 Log(T)$$

$$+ 0.110 Log(\sigma_d) - 0.118 Log(\eta)$$

$$+ 0.930 Log(V_{beff}) + 0.501 Log(V_a)$$

where

σ_d = deviator stress, psi.

η = viscosity of the asphalt binder at 70°F, $\times 10^6$ poise.

V_{beff} = effective asphalt content by volume, percent.

V_a = air void volume, percent.

$$RD_{AC} = \sum_{i=1}^{N} (\varepsilon_p)_i \cdot \Delta h_i$$

RD_{AC} = rut depth at the asphalt concrete layer

N = number of sublayers

$(\varepsilon_p)_i$ = vertical plastic strain at mid-thickness of layer i

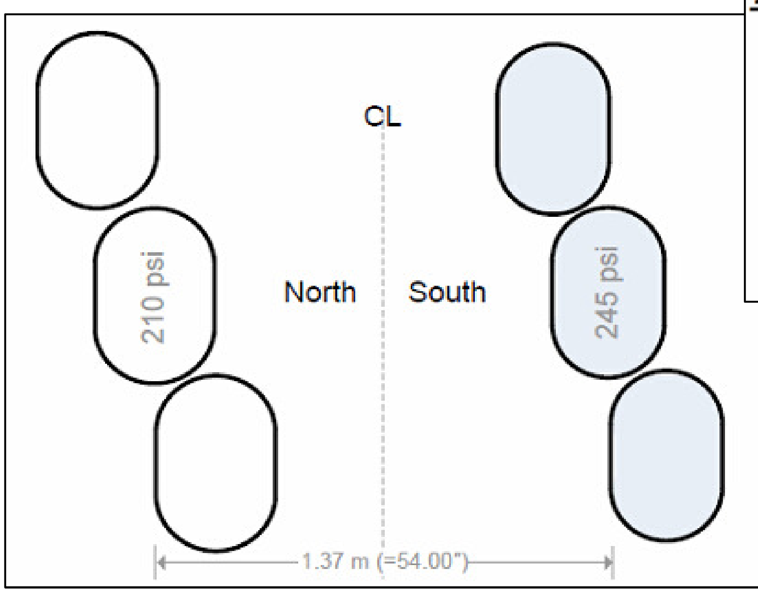
Δh_i = thickness of sublayer i

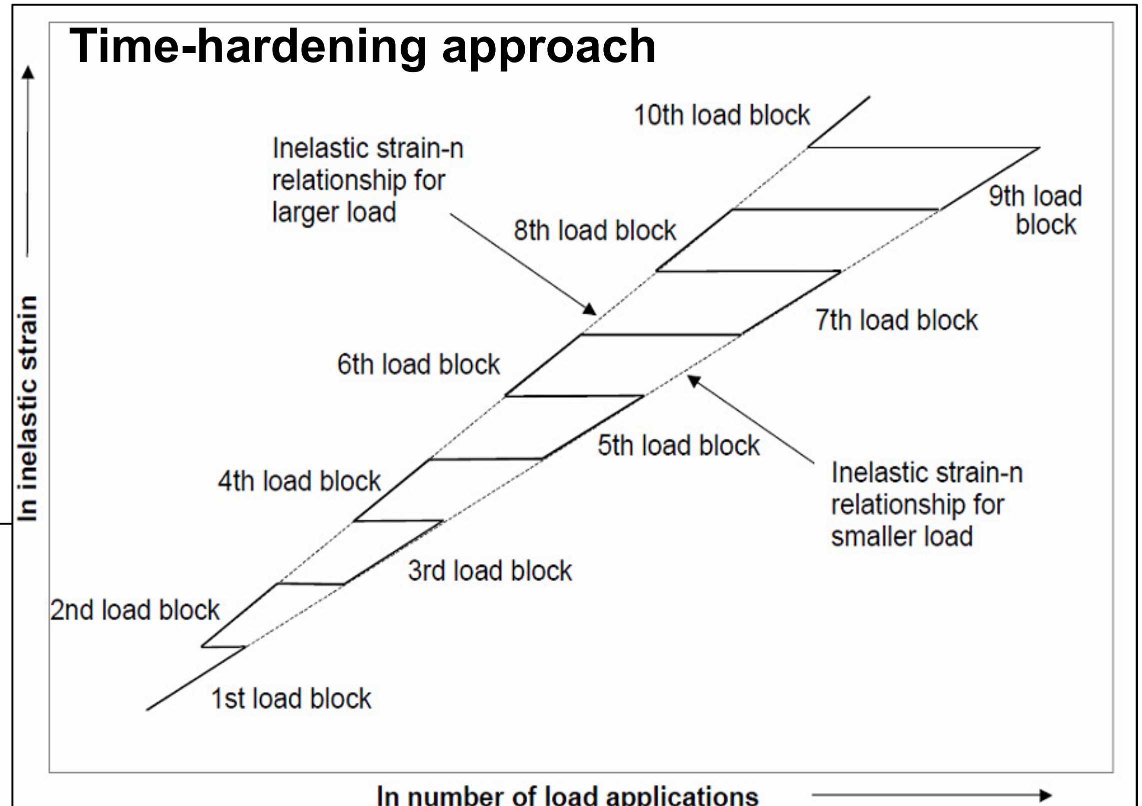
Effect of Tire Pressure on Rutting Depth

Tire load: 272.7kN (61.3kips)	AI Model			MEPDG model		
Tire pressure: Mpa (psi)	1.45 (210)	1.69 (245)	Change	1.45 (210)	1.69 (245)	Change
Rut depth (in.)	Measured temperature profile at NAPTF					
400th cycle	1.40	1.56	+11%	0.65	0.71	+9%
800th cycle	1.90	2.11	+11%	0.91	1.00	+10%
Rut depth (in.)	Reversed temperature profile					
400th cycle	1.55	1.74	+12%	0.77	0.85	+10%
800th cycle	2.09	2.35	+12%	1.08	1.19	+10%

Simulation of Wander Pattern

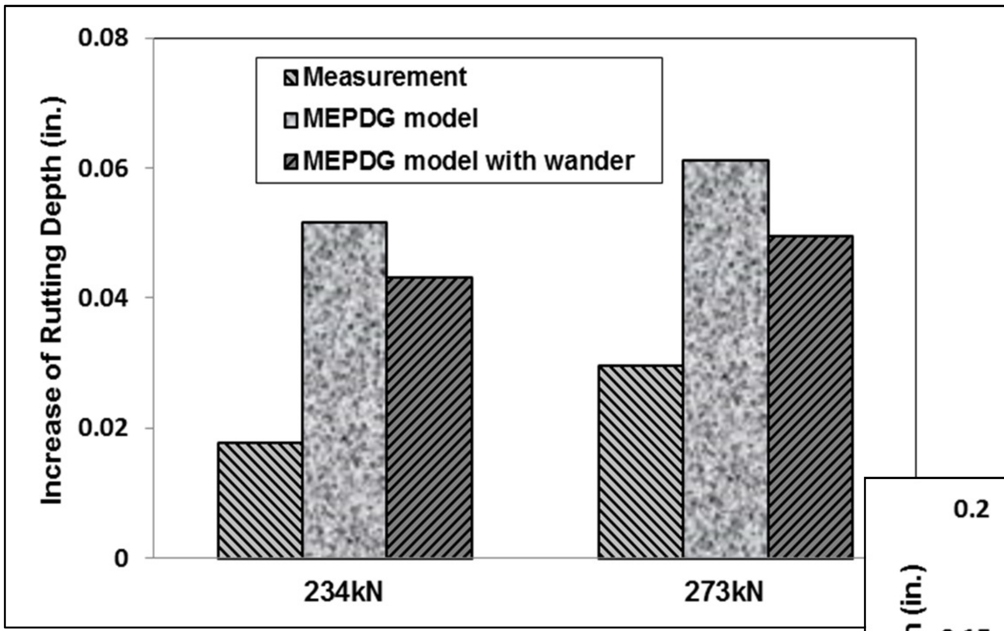
Wander during APT

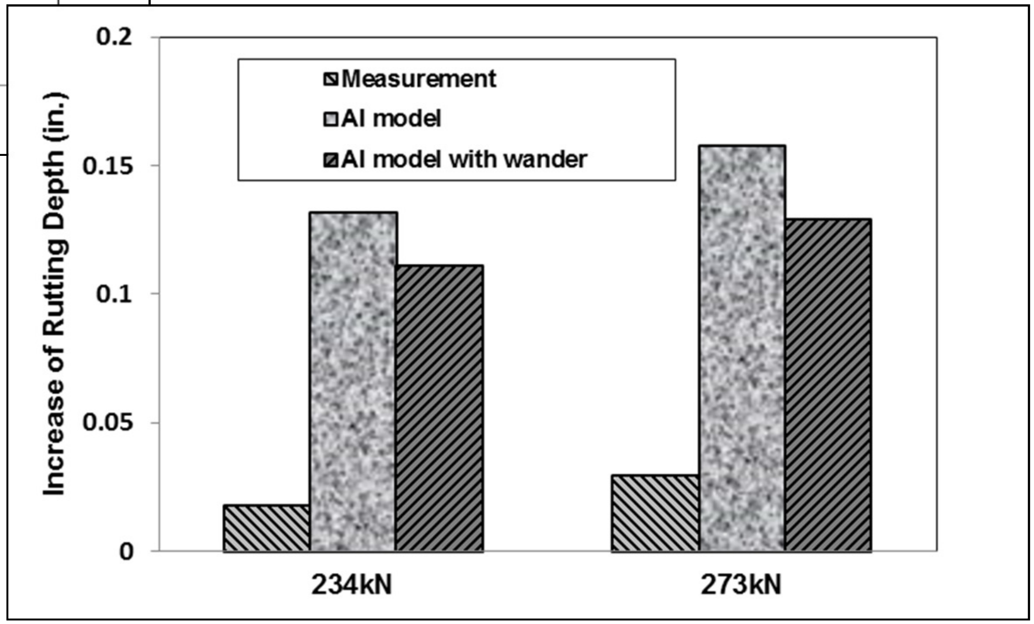




(*After Monismith et al. 2006*)

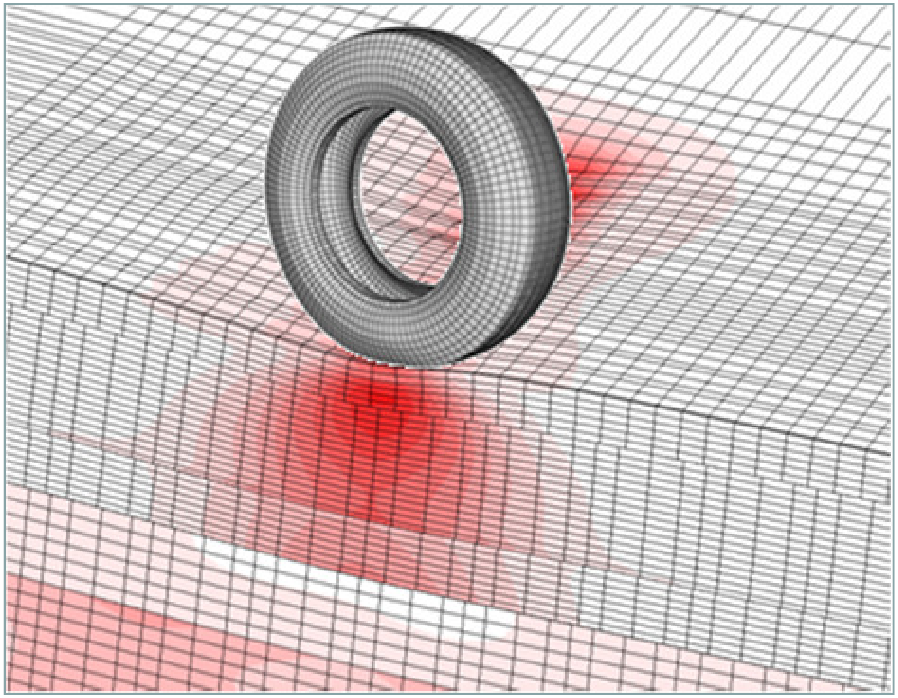
Effect of Wandering on Rutting





Conclusions

- **The high tire pressure causes greater responses by different percentages**
  - Temperature profile affects maximum pavement responses
  - Changes of maximum strain responses due to tire pressure are not affected by temperature variation
- **The high tire pressure causes slightly greater rutting depth**
  - Calibration is needed to predict accurate rutting depth



Thank You
Questions ?

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